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WADC TECHNICAL REPORT 52-282

THE PURKINJE EFFECT IN LUMINANCE MEASUREMENTS OF AIR FORCE PHOSPHORS

DANIEL I. POMERANTZ
JOHN R. CANNON

MATERIALS LABORATORY

OCTOBER 1952

WRIGHT AIR DEVELOPMENT CENTER

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WADC TECHNICAL REPORT 52-282

THE PURKINJE EFFECT IN LUMINANCE MEASUREMENTS OF AIR FORCE PHOSPHORS

Daniel I. Pomerantz
John R. Cannon

Materials Laboratory

October 1952

RDO No. 616-14

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared in the Materials Laboratory, Directorate of Research, Wright Air Development Center. The work reported was completed under Research and Development Order 606-63, subsequently 616-14, "Luminescent Phosphors", with Mr. D. I. Pomerantz acting as Project Engineer.

ABSTRACT

A formula is derived for relating effective and photopic units of luminance, making use of Weaver's interpolated data for the mesopic luminosity functions. This formula is applied to the spectra of four typical Air Force luminescent phosphors and the calculated results are compared with experimental data obtained at Wright Air Development Center. It is concluded that Weaver's data may tentatively be accepted for conversion between effective and photopic units in luminance measurements of luminescent materials.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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INTRODUCTION

It is perhaps surprising that a concept as useful as that of luminance (1)* has not been defined in an entirely unambiguous manner. This is probably due to the fact that the measurement of the luminance of an area, unlike the measurement of most physical quantities, involves a subjective judgment. The term luminance, as operationally defined, implies the projection onto a human retina of two adjacent images. One image is that of the surface whose luminance is to be measured. The adjacent image is that of a surface which has by international agreement been assigned a certain value of luminance. (2,3) The observer is then requested to vary the "brightness" of one or the other images until he feels the two are equally bright. The factor by which the energy which strikes unit area of the retina in each image has been varied may be measured in a precise manner. (4) The luminance of the unknown surface may be computed from these factors and the luminance of the standard surface.

It is known that the individual making the photometric match will find it easy if the two adjacent images are the same color. He merely varies one or the other until the dividing line between them disappears. But suppose the two are of different colors (heterochromatic). Clearly a large element of subjectivity is involved in deciding whether a red image is "brighter" or "less bright" than a white one. This difficulty with the definition of luminance suggests the question which must always be asked about an operational definition; namely, what factors, which have not been specified in the definition, will affect the results of the measurement? Such factors might be the variation existing in normal eyes, the shape of the retinal images, their size or position on the retina, the condition of adaptation of the eye, or metameric images, i. e. images having the same color but different spectral composition.

This last factor of metameric images contains the clue to the others. If the two images have identical spectral composition, then the other variables will have little or no effect on the result. In this case the eye is operating as a null instrument, i.e. determining the equality of two signals of exactly the same quality. If the two images are different in spectral composition, and particularly if they are differently colored, all the other variables suggested in the above questions and one other of utmost importance at low levels of illumination will affect the results to some measurable degree. This last variable, which may not at first be apparent, is the level of illumination of the retinal images themselves. Suppose a photometric match is made between two differently colored areas of low luminance. Then suppose the energy coming from both areas is reduced by half, but no other spectral change. Will the areas still appear to be equally bright? The answer in general is "No". The color nearer the blue end of the spectrum will be brighter when the illumination is reduced. This shifting of spectral sensitivity of the eye, known as the Purkinje effect, has been investigated by many observers. What is involved physiologically is a change from one type of receptor in the retina, the cones, to another, the rods, as the illumination level is reduced. During this process the peak of the spectral sensitivity curve of the eye shifts from 555 millimicrons toward shorter (bluer) wave lengths, approaching a limit of approximately 500 millimicrons at

* All psychophysical terms not defined in this report have the meanings given in reference (1)

the lowest visible levels.(1,5) The shape of this sensitivity curve at luminances above about one foot lambert (the photopic region) has been the subject of an international agreement based on the averaged observations of a great many normal observers. (6) As the luminance falls below one foot lambert the shadows progressively deepen. What few measurements have been made in this (mesopic) region do not agree very well.(5,7) At the very lowest levels of luminance (the scotopic region) there appears to be considerable disagreement between the results of various observers with evidence that the conditions of observation, such as the size of the field, affect the results quite pronouncedly.(5, 8, 12, 16)

The practical importance of luminance measurements in the mesopic region shows up in cases where it is necessary to illuminate instrument dials in such a way as to make them legible but not so bright as to affect the observers' ability to see in the dark.

In the light of the above mentioned ambiguities in the definition of luminance and of the pronounced consequences of the Purkinje phenomenon with spectra of high purity, it was believed important to measure this effect on luminance measurements of phosphors such as are used in marking aircraft instruments.

SECTION I

PURPOSE

The purpose of this report is to present factors of conversion between effective and photopic units of luminance for various spectral compositions and luminances. A method for computing such factors will be demonstrated. The method is applied to certain Air Force phosphors where spectra have been measured and the results are compared with experimental measurements on the same phosphors.

SECTION II

UNITS

Essentially two methods may be used to define a scale of luminances which extends below photopic levels, i.e. less than 1 foot lambert. In one instance a light source of specified quality may be adopted to be compared with all unknown luminances regardless of color. Once this has been done, the scale may be calibrated at one point in the photopic region by comparison with the international standard, and at all other values of luminance by reducing the radiance* of the viewed field in a known manner. (4) The results of measuring with such a scale are in units of "effective luminance" such as the "effective microlambert". (9, 10).

In another instance, one may adopt a different luminance scale for each different quality of radiation. Then, a photometric comparison field is produced emitting light of the same spectral distribution or quality as that from the area whose luminance is to be measured. The comparison field is calibrated against the international standard at some point in the photopic region. By reducing the radiance of the comparison field in a known manner one has a scale of luminance for one particular quality of light. The same procedure must be followed for light of each quality which is to be measured. The unit measured in such a manner will be called in this report a unit of "photopic luminance"** inasmuch as all heterochromatic matches involved in measuring luminance in this way are made at photopic levels. Thus, a constant photopic sensitivity curve is assumed. Such a unit is much more conveniently measured by photoelectric methods than effective luminance since each photosensitive surface has a sensitivity function independent of intensity.

There has been considerable debate over what quality of light source shall be used to define the unit of effective luminance as well as what other conditions of observation shall be specified (11, 12, 13). Without entering this debate, it would appear that American photometrists have little choice but to adopt the source used in calibrating their low luminance standards.

* All terms involving radiant energy used in this report have the meanings given in reference (4)

** This quantity has been called "equivalent brightness" in reference (9)

The source used by the National Bureau of Standards in the calibration of standards of luminance is an incandescent lamp with a color temperature of 2360° Kelvin. The conditions of measurement specify adaptation to the level of luminance being measured and a field subtending an angle greater than five degrees at the eye. The photometer used for this purpose is described in the Journal of Research of the National Bureau of Standards.(14) The unit of luminance resulting from the use of this photometer under the proper conditions (10) is called the "effective microlambert". All experimental results quoted in effective microlamberts in this report were obtained using the same photometer described in the above references.

It is a consequence of the Purkinje effect that the two scales of luminance will not coincide except in the photopic region. The ratio of one unit to the other will depend upon the luminance to be measured and on the spectral composition of the light. The more this varies from that of the standard 2360° K. source, the greater will be the difference between the two units. This difference is so great for light of some qualities as to make the specification of luminances in microlamberts highly misleading. Thus, if a red and blue area are both measured at one photopic microlambert, the blue will appear much brighter than the red and may be as much as ten times brighter when measured in effective microlamberts. Clearly the effective unit of luminance is more a measure of the visual effect of an area sending light to the eye. Consequently, this unit has been gaining popularity in the specification of low luminance values.

SECTION III

THEORY

Let us suppose curves are available on the spectral sensitivity or luminosity function of the eye at various luminances, i. e. plots of the inverse of the energy of monochromatic radiation required to produce the specified effective luminance. Call these data $y(B',\lambda)$ where B' is the specified luminance measured in effective units of luminance and λ is the wavelength of the radiation. Let us also suppose, as is usually the case, that such data are known only in relative units, i. e. the shapes of the curves for various luminances known but not their relative heights. For simplicity, let each curve of $y(B',\lambda)$ have a peak value of unity. Call $c(B')$ the unmeasured quantity giving the maximum height of the curve specified by B. Thus, the absolute luminosity function of the eye is given by $c(B')y(B',\lambda)$.

Consider an area emitting light with a spectral composition of radiance $E(\lambda)$. Then its effective luminance is:

$$B'=c(B')\int y(B',\lambda)\ E(\lambda)\ d\lambda \qquad (1)$$

(All integrals are carried over all visible wave lengths.) Equation (1) assumes that if the monochromatic luminances $c(B')\ y(B',\lambda)\ E(\lambda)$ be superimposed, the resulting luminance will be their sum, providing the luminosity function $y(B',\lambda)$ has been measured at the resultant field luminance. This is known as the "additivity law at constant field luminance" and has been shown experimentally to be exact.(15, 19)

In equation (1) if $y(B',\lambda)$ is in units of lumens per watt, and $E(\lambda)$ in watts

per square centimeter per unit solid angle, then B' is in units of effective lamberts. The luminance of the same area in units of photopic lamberts, designated B, is by definition:

$$B = c(B_o) \int y(B_o, \lambda)\ E(\lambda)\ d\lambda \qquad (2)$$

Here B_o is any photopic luminance and hence $y(B_o\lambda)$ is the sensitivity curve adopted by the International Commission on Illumination. $c(B_o)$ is generally taken numerically as 625 making the peak luminosity of the photopic curve 625 lumens per watt. In effect this quantifies the lumen.

In order to derive an equation for B'/B from (1) and (2) it is necessary to evaluate the constant c(B'). This may be done by considering the standard scale of luminance, an area emitting light of the quality of an incandescent lamp at a color temperature of 2360° K. For this area, the luminance is the same in both systems of units since both are defined in the same way (see Part II). That is, for any point on the standard scale:

$$B' = B \quad (\text{at } 2360^\circ\ \text{K}) \qquad (3)$$

Calling $E_o(\lambda)$ the spectral composition of radiance from the standard, (3) may be written out explicitly in terms of (1) and (2),

$$c(B') \int y(B', \lambda)\ E_o(\lambda)\ d\lambda = 625 \int y(B_o \lambda)\ E_o(\lambda)\ d\lambda \qquad (4)$$

whence,

$$c(B') = \frac{625 \int y(B_o, \lambda)\ E_o(\lambda)\ d\lambda}{\int y(B', \lambda)\ E_o(\lambda)\ d\lambda} \qquad (5)$$

Inserting c(B') in (1) the effective luminance is given by:

$$B' = \frac{625 \int y(B', \lambda)\ E(\lambda)\ d\lambda \int y(B_o, \lambda)\ E_o(\lambda)\ d\lambda}{y(B', \lambda)\ E_o(\lambda)\ d\lambda} \qquad (6)$$

In terms of the absolute luminosity function:

$$K(B', \lambda) = c(B')\ y(B', \lambda) \qquad (7)$$

B' may be written

$$B' = \int K(B', \lambda)\ E(\lambda)\ d\lambda \qquad (8)$$

Finally the ratio of effective luminance to photopic luminance is given by,

$$\frac{B'}{B} = \frac{\int K(B',\lambda)\ E(\lambda)\ d\lambda}{625\int y(B_o,\lambda)\ E(\lambda)\ d\lambda} \qquad (9)$$

$$\frac{B'}{B} = \frac{\int y(B',\lambda)\ E(\lambda)\ d\lambda\ \ y(B_o,\lambda)\ E_o(\lambda)\ d\lambda}{\int y(B',\lambda)\ E_o(\lambda)\ d\lambda\ \ y(B_o,\lambda)\ E(\lambda)\ d\lambda} \qquad (10)$$

It is seen that to calculate B'/B, only the relative luminosities $y(B',\lambda)$ at various luminances need be known. What is more, $E_o(\lambda)$ and $E(\lambda)$ need be known only in relative energy units since any factor multiplying $E_o(\lambda)$ or $E(\lambda)$ would appear in both the numerator and denominator of (10).

The expression (9) for B'/B may be seen to have a further significance. If both numerator and denominator of (9) are divided by the total energy of the source, $E(\lambda)\ d\lambda$, are respectively the luminosity or luminous efficiency of the source at level B' and its luminosity at level B_o, photopic luminosity. The ratio of these two quantities will still be equal to B'/B and may be called the relative luminosity or relative efficiency of the source $E(\lambda)$ as a function of luminance level. This quantity depends, of course, on the quality of the source adopted as standard.

SECTION IV

COMPUTATIONS

The data on $y(B',\lambda)$ which have been used in calculating B'/B are those of K. S. Weaver (15) which were obtained by interpolation between the photopic and scotopic luminosity functions. The consensus of American opinion would appear to favor the acceptance of these data provisionally for mesopic and scotopic luminances (11). Table I of Weaver's paper gives $y(B',\lambda)$ as defined previously in Section IV of this report. The first column of Table I is $y(B_o,\lambda)$, the I. C. I. adopted function. Table III of Weaver's paper gives $K(B',\lambda)$ as defined by equation (7). Using these data and the values of $E(\lambda)$ measured as described below, B'/B was calculated from equation (9). Following the terminology of this report the horizontal variable in Weaver's tables would be called "Log effective luminance", rather than "Log luminance".

In Figures 6,7, 8, and 9, B'/B is plotted versus B' in effective microlamberts for each of the four phosphors measured. (1 effective lambert = 1.076 effective foot-lamberts.) Figure 10 shows the variation of B'/B versus B' for all four of the phosphors measured.

SECTION V

EXPERIMENTAL PROCEDURE

Spectral Energy Measurements

For measuring the spectral energy distribution of the four phosphors, Figures 2, 3, 4, and 5, a spectroradiometer was assembled using a Zeiss Constant Deviation Monochromator with a Type 1P22 photomultiplier phototube mounted at the exit slit. While this tube is less sensitive at its peak value than some types, it was chosen for its relatively high red sensitivity and its spectral sensitivity characteristic being less strongly peaked, thereby reducing the error introduced by changes in the width of the monochromator band pass. The output of the photomultiplier was measured with a Photovolt Photometer, Model 512. Due to the considerable variations in photomultiplier tubes and the unknown transmission characteristics of the monochromator, it was considered necessary to obtain a sensitivity curve for the combination rather than use the curve published for the 1P22 photomultiplier tube alone. This was done making use of a tungsten standard at 2848° Kelvin color temperature. In this procedure, the filament of the standard lamp was imaged on the entrance slit of the monochromator by a condensing lens which was made large enough that the entrant beam completely filled the collimating lens of the monochromator (17). In order to maintain a resolution which did not vary widely with wave length, the band pass of the monochromator was kept approximately constant by adjusting the width of the exit slit to be inversely proportional to the dispersion of the monochromator at each wave length measured. The entrance slit was kept constant but narrower than the exit slit so that its contribution to the band pass was smaller. The resulting resolution varies from about 5.0 millimicrons at 400 millimicrons to 5.3 millimicrons at 700 millimicrons. The sensitivity curve of the spectroradiometer was computed as the ratio of the photomultiplier output at a particular wavelength setting of the monochromator to the spectral intensity of black body radiation at 2848° K. No attempt was made to correct for the slight variation in the emissivity of tungsten over the visible range. The resulting sensitivity curve is presented in Figure 1.

The phosphors selected for measurement were representative samples of fluorescent luminescent materials which have conformed to Specifications AN-L-1a, Color 65, (Pale Yellow) and Air Force Specification 14157 and Amendment 1, Colors 63 (Vivid Green), 66 (Red), and 68 (Blue). Areas uniformly painted with these phosphors were placed so that the luminescence radiation would fill the collimating lens of the monochromator. The phosphor surfaces were illuminated by an ultraviolet lamp, model BL-2, manufactured by Black Light Products. This lamp consists of a General Electric FL4 Projector Flood mercury arc lamp with a filter transmitting only the ultraviolet component of the lamp output. The lamp was run from a constant voltage transformer and was permitted to warm up for one half hour before being used.

In measuring the spectra of the four phosphors, the exit slit was maintained at the same values for which the radiometer was calibrated in order not to introduce any error of the slit micrometer. Due to the relatively low brightness of the phosphors, the entrance slit was opened to .40 millimeters in order to obtain measurable output of the phototube. Under these conditions the band pass of the monochromator varies from about 7 to about 20 millimicrons as the wavelength varies from 400 to 700 millimicrons. The resulting spectra of the four phosphors are given in Figures 2, 3, 4, and 5. The ordinates are in relative units of energy per unit wavelength with a peak value adjusted to be 100.

Photometric Measurements

The apparatus used for determining the ratio B'/B experimentally is shown in Figure 11. The panel (A), uniformly coated with the phosphor to be studied, was illuminated by the ultraviolet lamp(B). This lamp was the same one used for making the spectral energy measurements. It has been moved closer to the panel in Figure 11 than was actually the case when used. Part of the phosphor area was illuminated directly by the lamp. The other part, for which B'/B was to be determined was illuminated through the filters held in the holder (C). These filters were chosen so that appropriate combinations would reduce the brightness of the unknown area in convenient steps. Stacks of 2 by 3 inch microscope slides and neutral Wratten filters were used. This area was observed as the comparison field in the NBS Wide Angle Photometer (D) described in reference (14). The same area was also observed as one half of the field of the Pulfrich aperture photometer (E). A description of this instrument may be found in reference (18). The other half of the Pulfrich Photometer field was illuminated by the directly irradiated area of the phosphor which serves as a reference luminance.

Preliminary tests were conducted to observe if any color difference appeared between the two halves of the field owing perhaps to the difference in level or quality of ultraviolet excitation. No color difference was observed in any of the phosphors over the entire range measured. It was possible that some color difference may have existed at the lowest levels measured without being detected, owing to the reduced ability of the eye to distinguish colors at these levels.

By determining the ratio of apertures of the two beams of the photometer necessary to equalize the luminances of the two halves of the field, the luminance of the unknown area referred to the reference area may be determined. Since the match is homochromatic the result is proportional to the luminance of the unknown area in photopic units of luminance. This procedure was followed for all four phosphors, making use of combinations of filters to produce approximately equal steps in luminance over the range to be measured. Ten readings were taken by one observer for each phosphor at each luminance level. The average value of the ten readings was taken as proportional to B.

Using the same conditions of excitation, the effective luminance of the unknown area was then measured. The proper current to yield radiation of color temperature 2360° K. from the photometer lamp was determined making use of the spectroradiometer described previously. It was found that the non-neutral characteristics of the two pieces of opal diffusing glass used in the photometer could be corrected by a Wratten filter No. 78C, the combination having a substantially flat transmission curve. The instrument was then calibrated at this current against a standard of approximately the same color temperature which had been calibrated by the National Bureau of Standards. The effective luminance of the test area was then measured. Each observer was dark adapted for at least 40 minutes before making readings and then, starting at the lowest luminance, made five readings at each luminance to be measured. In this way the eye was adapted to the level of luminance it was measuring. Fixation was natural (13). The ratio of the measurements described above is a quantity proportional to B'/B. The factor of proportionality for each phosphor could be determined from any point on the calculated curves for that phosphor (Figures 6, 7, 8, and 9) for which an observation had been made. The point chosen in each case was such to yield the best fit between the experimental points and the curves. The individual points of each observer are plotted in Figures 6, 7, 8, and 9. Three observers made measurements on the blue and green phosphors where the match was highly heterochromatic. Only one observer made measurements on the yellow and red phosphors where the match was more nearly homochromatic. Figure 10 shows the averaged results of all observers.

SECTION VI

CONCLUSIONS

As expected, the individual determinations of B'/B reveal a considerable dispersion around their mean value, the effect being more pronounced as the match becomes more heterochromatic. However, the averaged results of different observers yield rather good agreement with curves of B'/B calculated from Weaver's interpolation between photopic and scotopic luminosity data (15). It is concluded that these data may be accepted tentatively as satisfactory for conversion between photopic and effective units of luminance of Air Force luminescent materials.

The only departure from the calculated curve which is considered greater than the errors of the measurements appears in the green phosphor, Color 63, below about eight effective microlamberts. It is not possible to determine, without further experimental work, whether this deviation represents a deficiency in Weaver's method of interpolation or is an experimental error. If experimental, a deviation in this direction could be explained ~~if~~ the spectrum of the green phosphor were so pure that its width approached the band pass of the spectroradiometer. (The green phosphor has the purest spectrum of those measured.) In this case a spectrum of less than the actual purity would have been indicated and the calculated values of B'/B would be misleadingly low. Another possible explanation for this deviation would be a shift of the spectrum toward the blue as the level of excitation of the phosphor is reduced.

Figure 10 shows clearly the effect of color on the consequences of the Purkinje effect. Thus, as expected, the colors furthest removed from that of the standard 2360° K. source, such as the blue and red phosphors, show the most pronounced change in B'/B as the luminance is decreased. Interpreted in terms of luminosity, the blue phosphor produces more than four times as much visual response (modulus 2360° K.) per unit energy at the lowest luminances than at luminances above a foot-lambert, while the red phosphor produces only about one-fifth as much.

From the curves of Figure 10 one can see qualitatively what the effect would be of adopting another source as standard. If a source bluer than 2360° K. were to be adopted, all the curves would be moved downward, and vice versa for a source redder than 2360°K., such as the proposed source maintained at the freezing point of platinum.

In Figure 10 it is interesting to note the near coincidence of the curve of B'/B for Color 65 with the horizontal axis for which B'/B = 1, the curve of the standard source. This points to the interesting possibility of using this type of phosphor in radioactively excited luminance standards. In a photometer making use of apertures or neutral wedges to reduce its luminance, this type of standard would produce results very nearly equal to those obtained using a standard 2360° K. source. Such a phosphor would offer a more satisfactory color match with some materials. It is possible that phosphors may be developed with B'/B departing even less from unity over an appropriate range of luminances than the one which has been studied.

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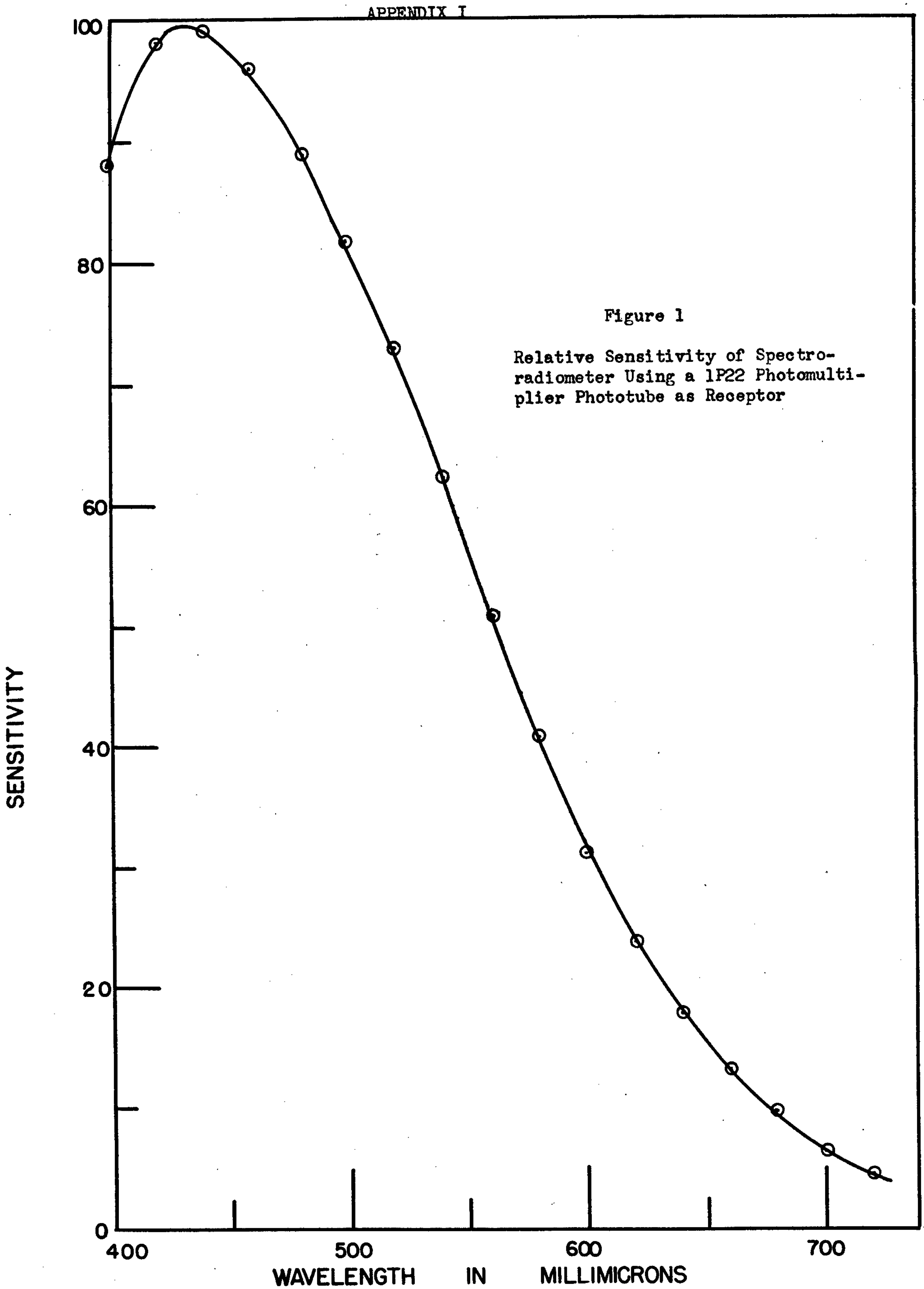

Figure 1

Relative Sensitivity of Spectroradiometer Using a 1P22 Photomultiplier Phototube as Receptor

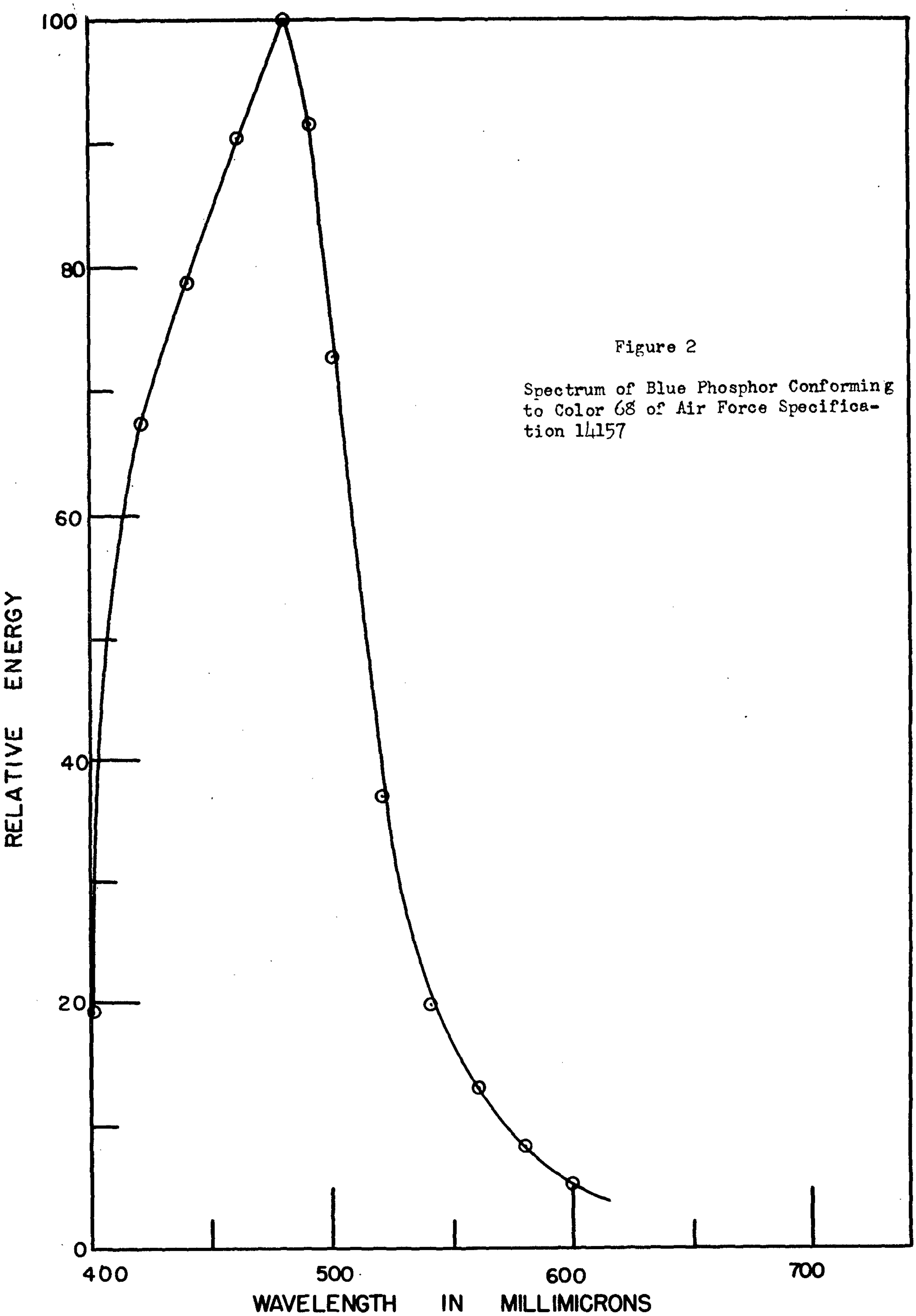

Figure 2

Spectrum of Blue Phosphor Conforming to Color 68 of Air Force Specification 14157

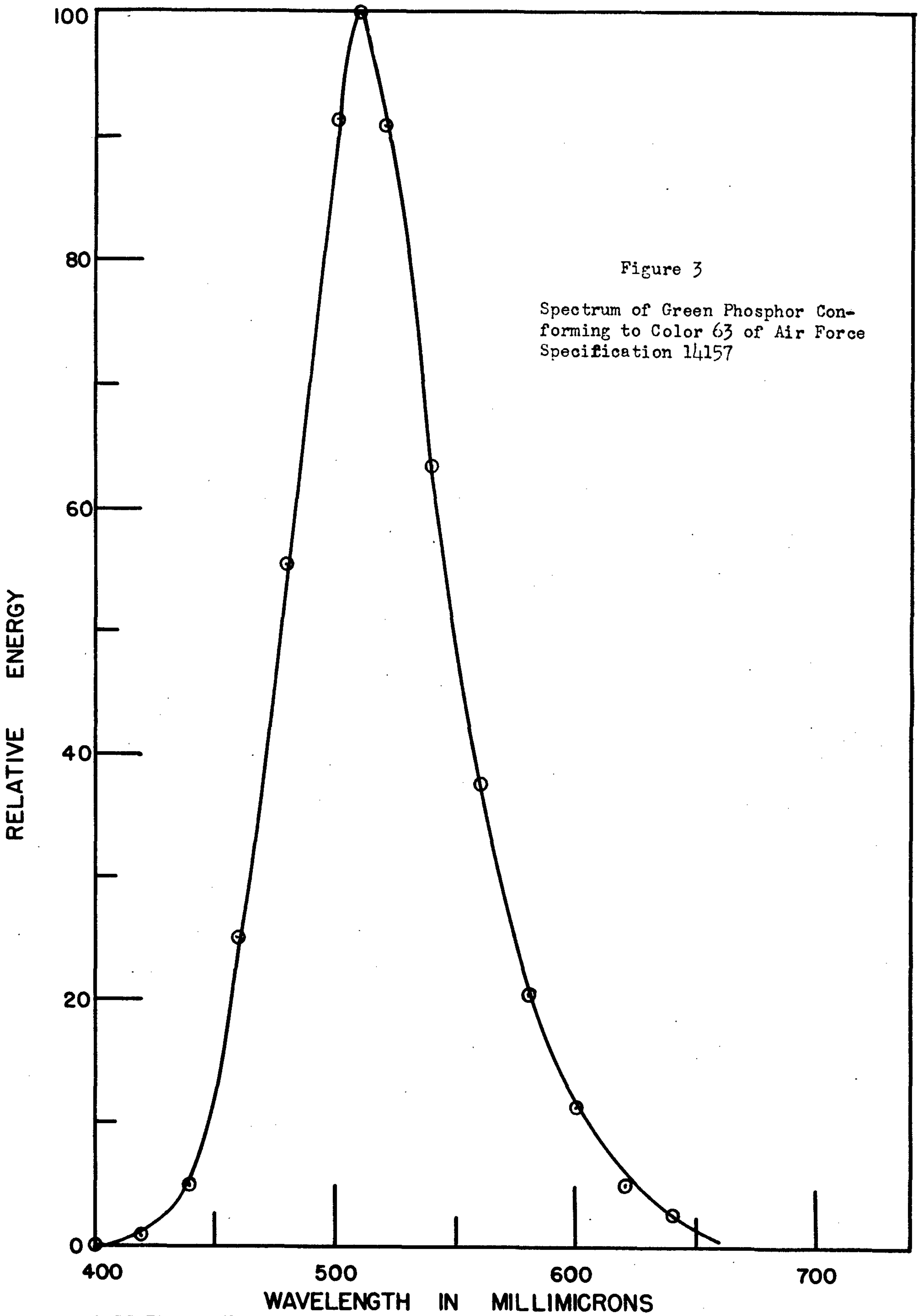

Figure 3

Spectrum of Green Phosphor Conforming to Color 63 of Air Force Specification 14157

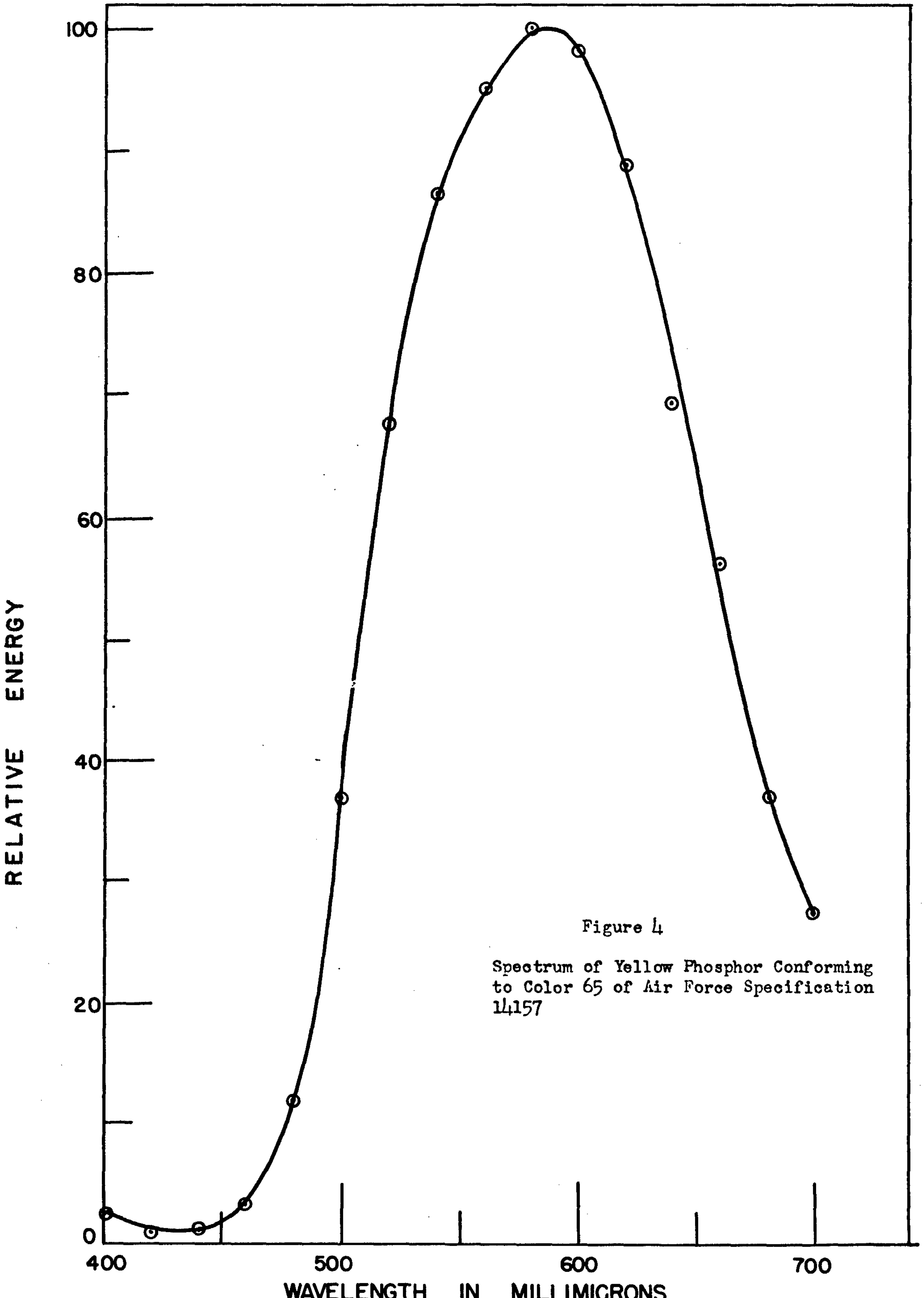

Figure 4

Spectrum of Yellow Phosphor Conforming to Color 65 of Air Force Specification 14157

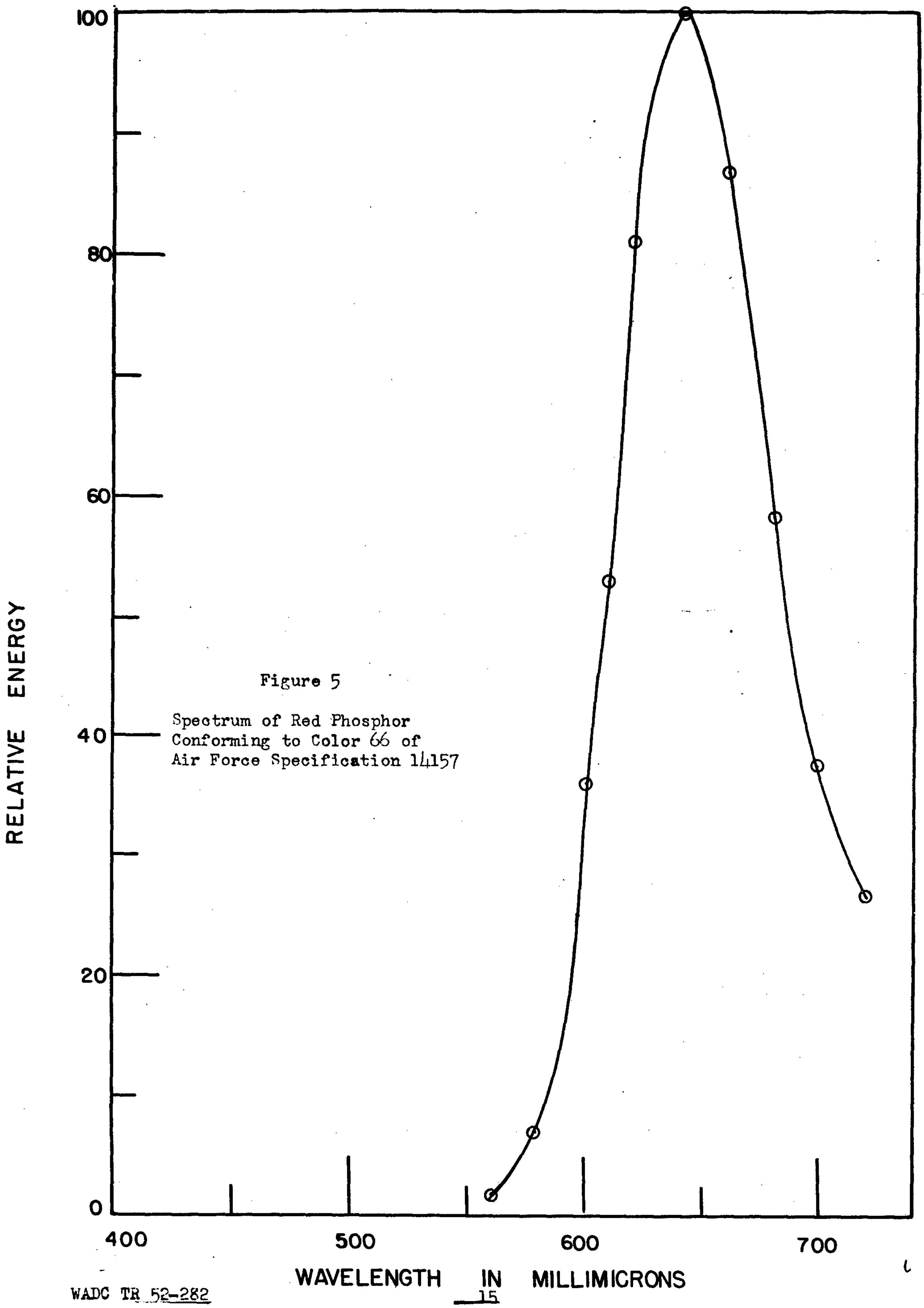

Figure 5

Spectrum of Red Phosphor
Conforming to Color 66 of
Air Force Specification 14157

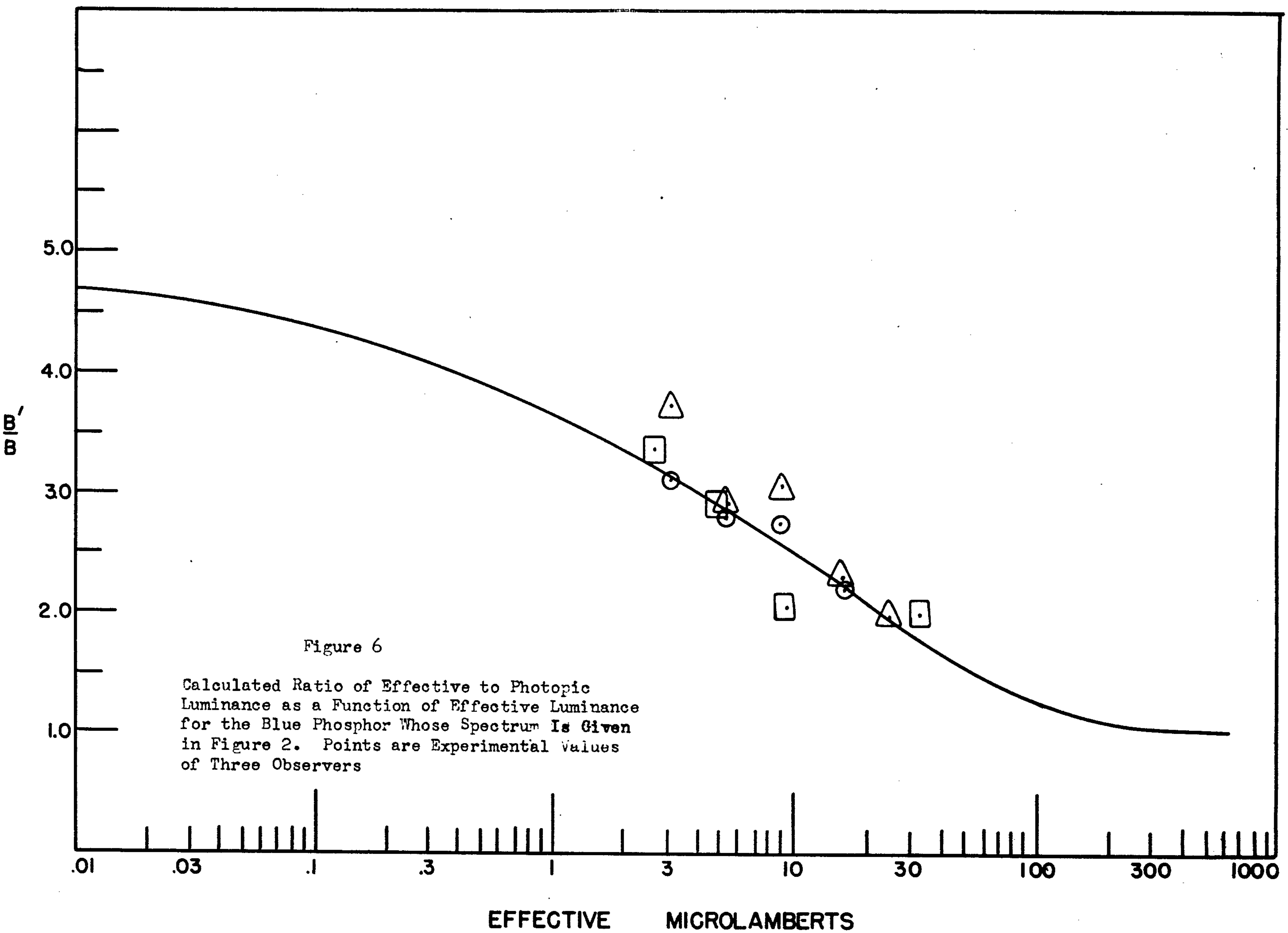

Figure 6

Calculated Ratio of Effective to Photopic Luminance as a Function of Effective Luminance for the Blue Phosphor Whose Spectrum Is Given in Figure 2. Points are Experimental Values of Three Observers

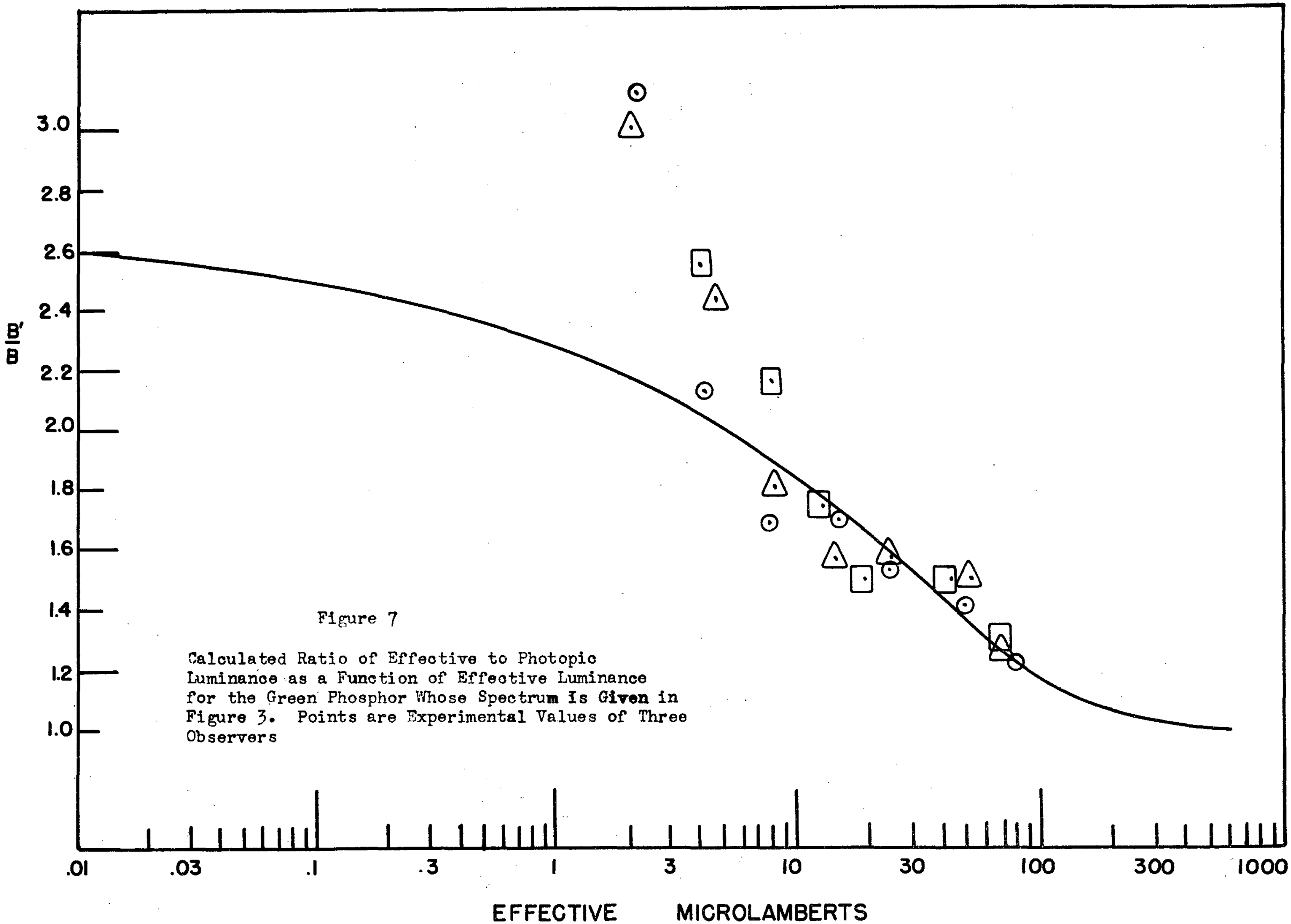

Figure 7

Calculated Ratio of Effective to Photopic Luminance as a Function of Effective Luminance for the Green Phosphor Whose Spectrum Is Given in Figure 3. Points are Experimental Values of Three Observers

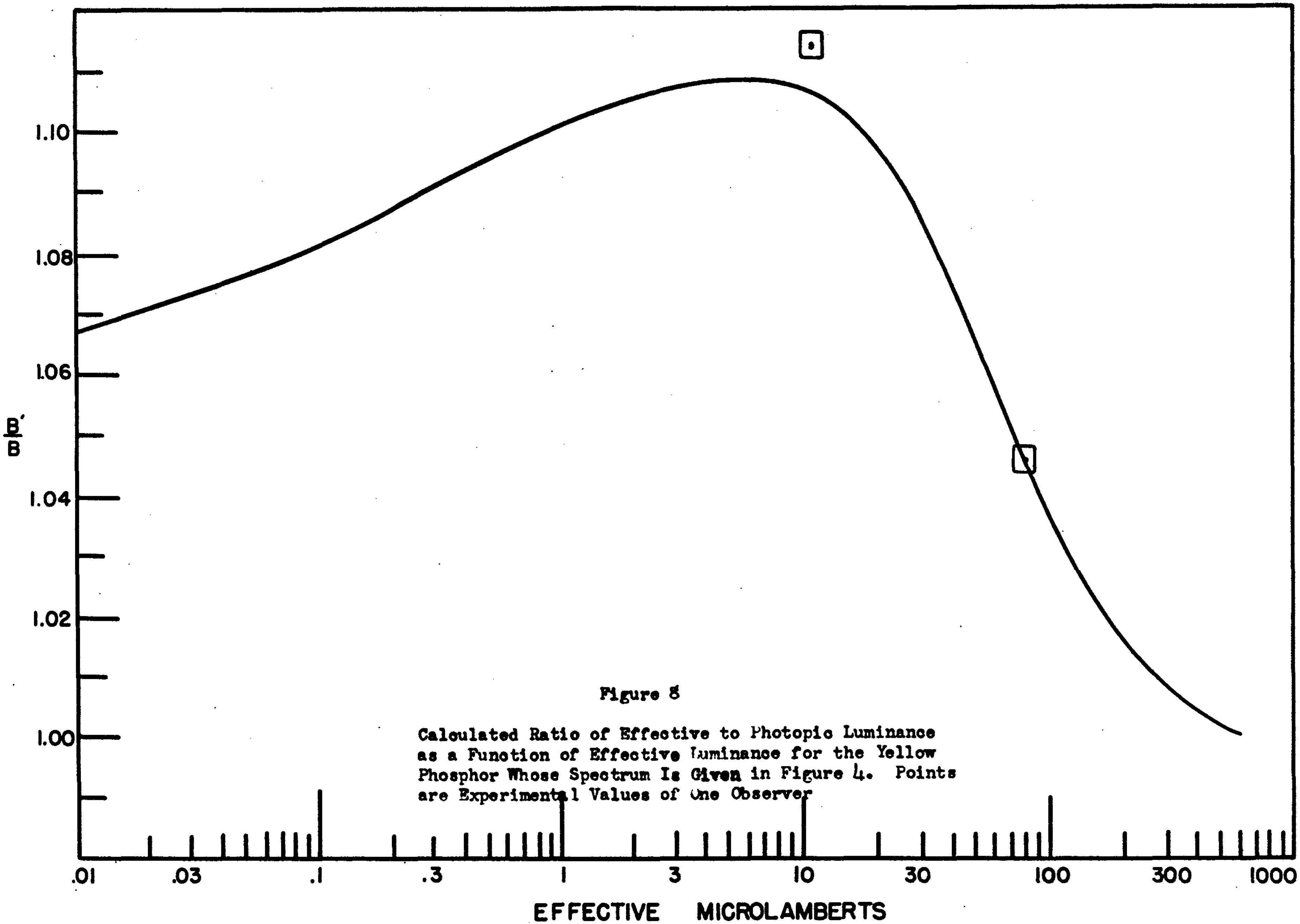

Figure 8

Calculated Ratio of Effective to Photopic Luminance as a Function of Effective Luminance for the Yellow Phosphor Whose Spectrum Is Given in Figure 4. Points are Experimental Values of One Observer

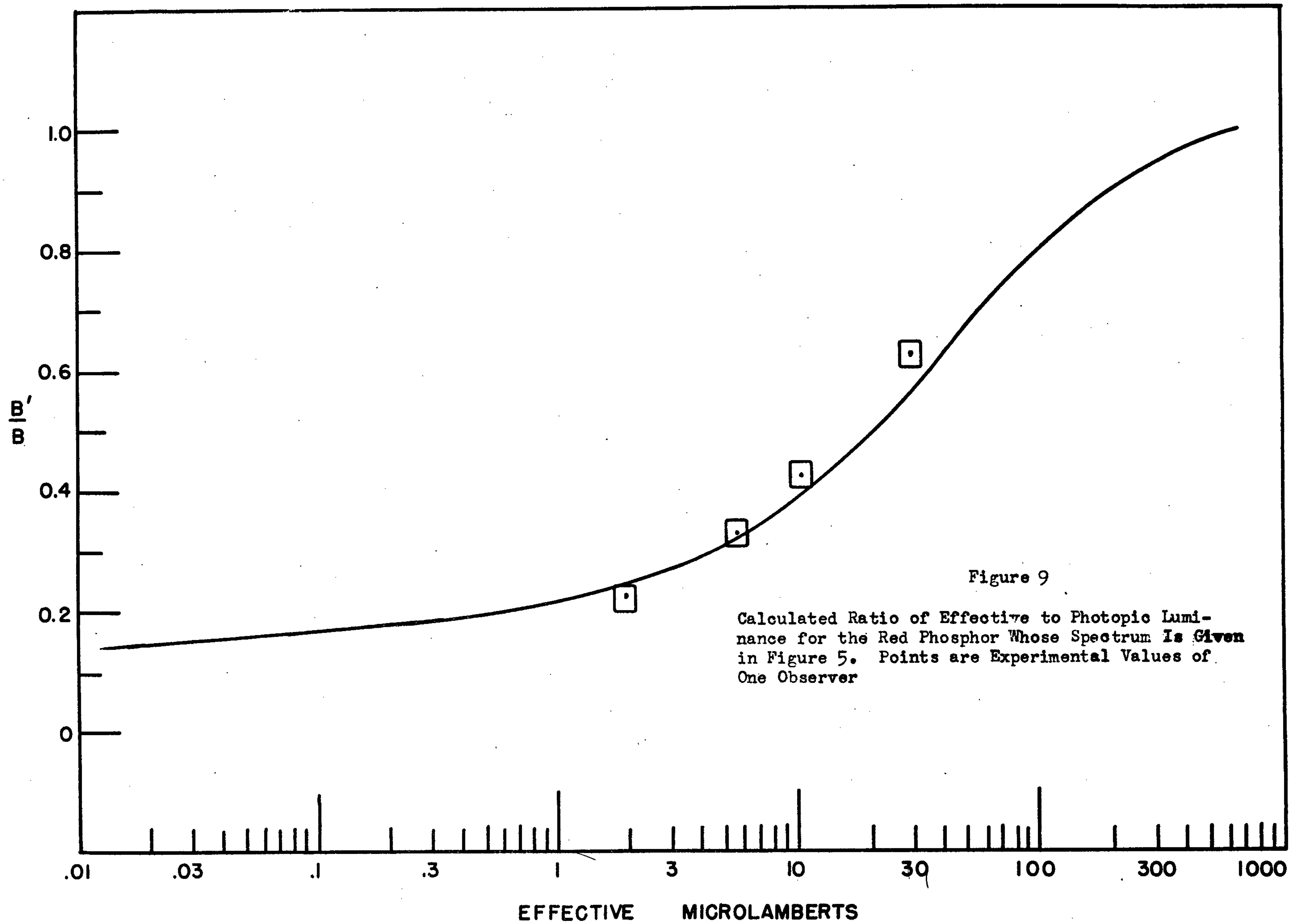

Figure 9

Calculated Ratio of Effective to Photopic Luminance for the Red Phosphor Whose Spectrum Is Given in Figure 5. Points are Experimental Values of One Observer

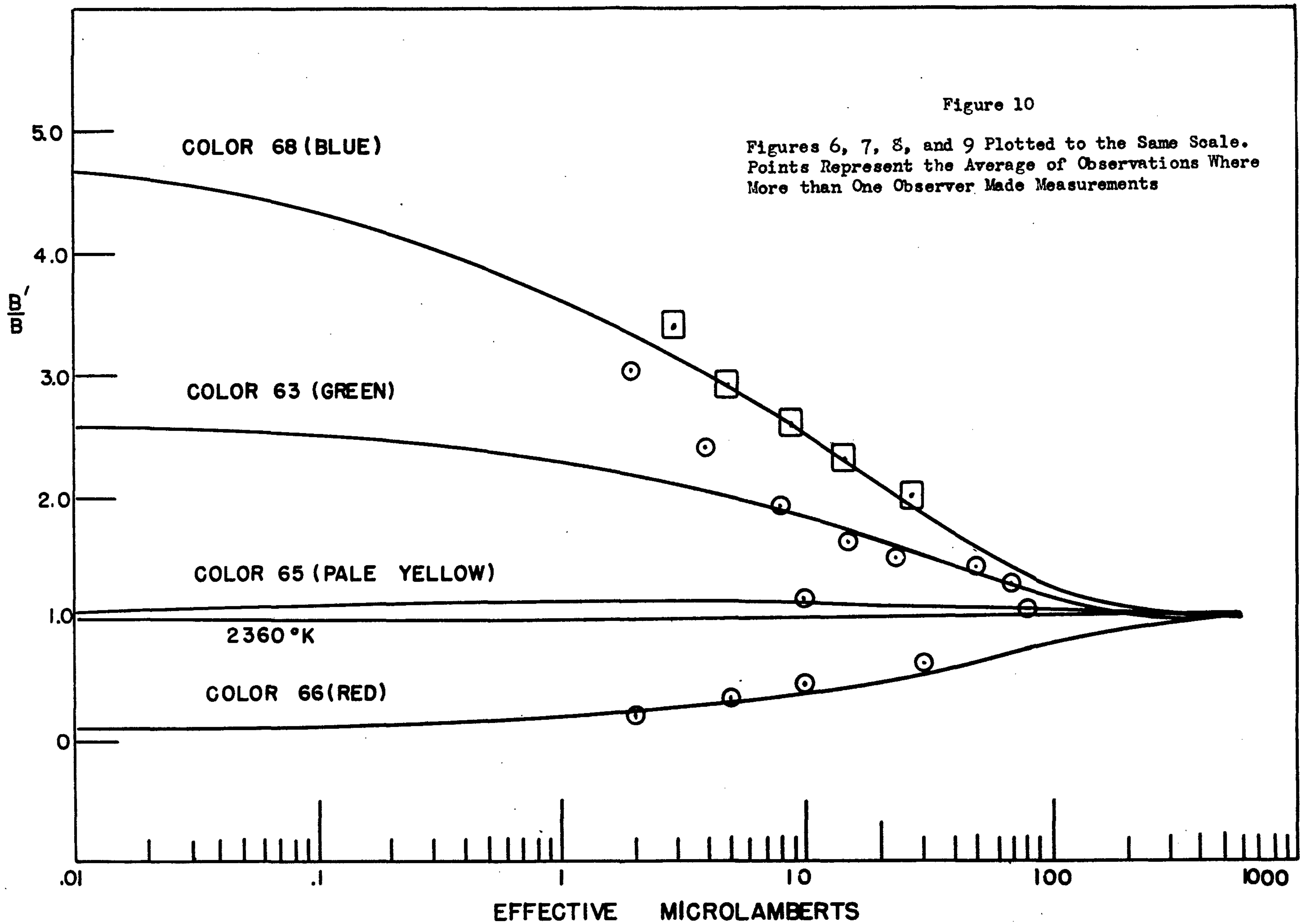

Figure 10

Figures 6, 7, 8, and 9 Plotted to the Same Scale. Points Represent the Average of Observations Where More than One Observer Made Measurements

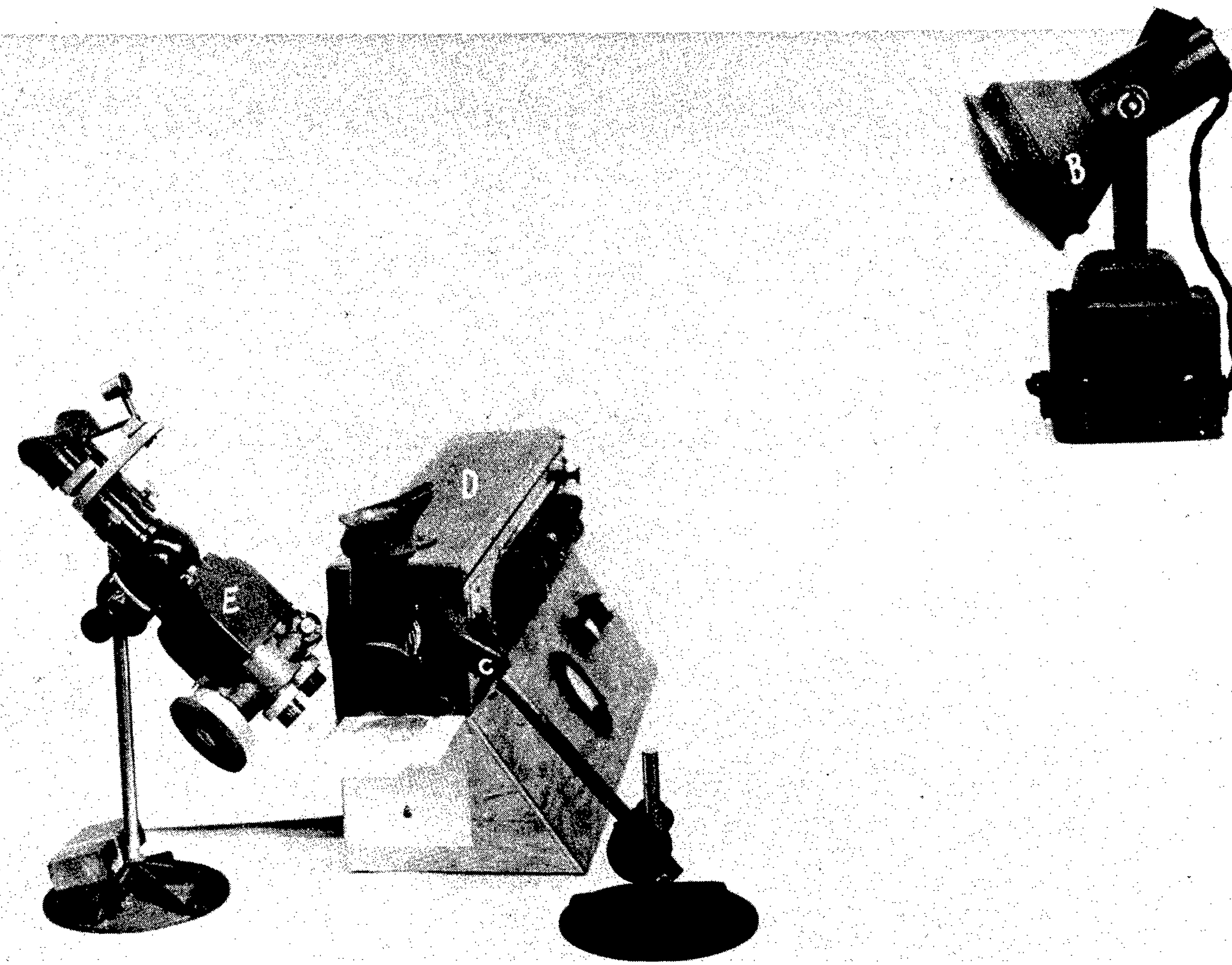

Figure 11

Experimental Arrangement for Determining the
Ratio of Effective to Photopic Luminance of the Various Phosphors